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THE EFFECT OF ALLOY COMPOSITION AND PROCESSING ON THE STRUCTURE AND PROPERTIES OF I/M Al-Li-X ALLOYS

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FINAL REPORT

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The major objectives of this program were to characterize the microstructure, deformation and fracture modes of Al-Li-X alloys with emphasis on determining the relationships between alloying elements, processing parameters, microstructure, and deformation and fracture behavior. We have found that the growth mechanism of T_1 precipitate plates occurs by the diffusional glide of Shockley partials on (111) matrix planes and that the growth ledges migrate by the ledge-kink mechanism. Plastic deformation prior to aging was shown to decrease the T_1 plate length and thickness, increase the number density by almost two orders of magnitude, increase the yield strength by 100 MPa while simultaneously reaching peak strength in 20% of the time required without plastic deformation. Plastic deformation prior to aging was shown to have a similar effect on S' precipitation in Al-Cu-Li alloys containing Mg; however, the deformation

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does not affect the size or fraction of grain boundary precipitates. Plastic deformation prior to aging primarily affects the aging kinetics of the strengthening phase, leading to an improved yield strength/ductility combination at peak strength when compared with material that is not given pre-age plastic deformation. The icosahedral T_2 phase formed at aging temperatures above 170°C. Since this phase decreases the fracture resistance, aging temperatures below 170°C are preferred for Al-Li-Cu alloys.

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THE EFFECT OF ALLOY COMPOSITION AND PROCESSING ON THE STRUCTURE AND PROPERTIES OF I/M Al-Li-X ALLOYS

I. ABSTRACT

The major objectives of this program were to characterize the microstructure, deformation and fracture modes of Al-Li-X alloys with emphasis on determining the relationships between alloying elements, processing parameters, microstructure, and deformation and fracture behavior. We have found that the growth mechanism of T_1 precipitate plates occurs by the diffusional glide of Shockley partials on (111) matrix planes and that the growth ledges migrate by the ledge-kink mechanism. Plastic deformation prior to aging was shown to decrease the T_1 plate length and thickness, increase the number density by almost two orders of magnitude, increase the yield strength by 100 MPa while simultaneously reaching peak strength in 20% of tne time required without plastic deformation. Plastic deformation prior to aging was shown to have a similar effect on S' precipitation in Al-Cu-Li alloys containing Mg; however, the deformation does not affect the size or fraction of grain boundary precipitates. Plastic deformation prior to aging primarily affects the aging kinetics of the strengthening phase, leading to an improved yield strength/ductility combination at peak strength when compared with material that is not given pre-age plastic deformation. The icosahedral T_2 phase formed at aging temperatures above 170°C. Since this phase decreases the fracture resistance, aging temperatures below 170°C are preferred for Al-Li-Cu alloys.

II. INTRODUCTION

High strength aluminum alloys are used for many types of Army air and ground transportation systems. A significant need exists to reduce weight in these systems in order to realize subsequent reduction in fuel use and cost. This need, combined with the constant demand for critical property improvement of materials used for these applications, are the basis for the active interest in Al-Li alloys (1-5). The addition of lithium to an aluminum alloy results in a six percent increase in the elastic modulus and a three percent decrease in density for each weight percent of lithium added to the alloy. The lower density aluminum-lithium alloys provide an alternative to the conventional 2XXX and 7XXX alloys currently being used in transportation structures. Furthermore, the successful history of aluminum alloys in transportation structures favors these low density alloys over polymeric and metal matrix composite structures. Like all alternatives, however, there are disadvantages as well as advantages and early Al-Li-Cu alloys had the disadvantage of low ductility and fracture toughness as well as production difficulties. Extensive research of Al-Li-X systems, that began in the early 1970's, has provided numerous breakthroughs in our understanding of these complex alloys and has led to the development of a number of commercially viable aluminum-lithium products.

This document is our Final Report on U.S. Army Contract Number DAAL03-86-K0128, "The Effect of Alloy Composition and

Processing on the Structure and Properties of I/M Al-Li-X Alloys". The major objectives of this program have been to characterize the microstructure, deformation, and fracture modes of Al-Li-X alloys with emphasis on determining the relationships between the alloying elements, processing parameters, microstructure, and deformation and fracture behavior. The research results obtained on this program should aid in the development of Al-Li alloys having density, strength, stiffness, and ductility combinations needed for high performance transportation systems. The results have already aided in the modification of processing of 8090 so that it could be used successfully in a system constructed by Lockheed Missiles and Space Company for the United States Government. Processing procedures developed under this research program have been adopted by the commercial producers of Al-Li alloys.

III. ACCOMPLISHMENTS

A. **Heterogeneous Precipitation and Mechanical Properties in Al-Li-Cu Alloys:** From the experimental work performed during this study of heterogeneous precipitation in an Al-2.4Li-2.4Cu-0.18Zr alloy the following conclusions may be drawn:

1. A single plate shaped precipitate phase (T_1) is observed in the microstructure on aging for various times at 190°C. The T_1' phase previously reported (6-8) does not exist. This finding is based on the fact that the anomalous diffraction behavior observed by these investigators can be explained in terms of the T_1 structure.

2. Analysis of structure images shows that the T_1 unit cell is hexagonal with the reported cell parameters (9). Comparison of images with computer simulations based on the recently proposed atom positions (10) reveals that the chemical compositions of the individual (0001) planes within this cell are essentially correct. However, the placement of atoms on sites within planes apparently require further adjustments.

3. T_1 precipitate plates and material of stoichiometric T_1 composition (Al_2CuLi) both contain stacking defects on (0001) planes. The presence of compositional defects (i.e. stacking of wrong chemical layers) has been shown to occur in the precipitate plates. Evidence also exists for displacement (i.e., 1/6(112)) faulting between (0001) layers. Both types of faulting could conceivably cause the anomalous diffraction behavior observed for thick T_1 plate shaped precipitates.

4. Stretching the solutionized material prior to aging at 190°C can result in a 20-25% increase in observed yield stress at peak strength depending on the extent of the cold work.

5. Relative alloy strength is directly related to the T_1 volume fraction. Material stretched 4-8% will reach its peak strength 4-5 times faster than unstretched material.

6. The δ' formation kinetics are not significantly affected by enhanced T_1 precipitation in stretched material.

7. Stretching greatly increases the number of dislocation nucleation sites available for T_1 formation as evidenced by a large increase in T_1 number density. Material

stretched 8% has approximately a two order of magnitude increase in T_1 number density over unstretched material.

8. Shorter average plate lengths are observed in stretched material. This is a result of a more rapid decrease in matrix supersaturation caused by a greater number of growing plates. Also, the number of interacting plates on two or more variants increases with stretch level (i.e., plate intersections and impingement points).

9. Stretching tends to produce thinner plates on average than unstretched material. Again, this finding is related to the rate at which supersaturation is removed from the matrix. The nucleation of new growth ledges which thicken the plates depends on matrix supersaturation. Plate thickening continues after the matrix supersaturation is used up (coarsening), but at a slower rate.

10. Preaging material after stretching 6% for 24 hours at 50°C was found to produce a significant amount of T_1 prior to aging. The material would subsequently reach peak strength on aging at 190°C more quickly than material stretched 6% but not preaged. However, preaging probably does not significantly influence the peak aged yield stress between the two conditions.

11. The nucleation and growth of T_1 plates proceed by the proposed mechanism of dissociation of matrix dislocations into partials (1/6(112)) which form the growth interface of the plate and plate ledges (11).

12. Analysis of structure images reveals that the

initial nucleation of T_1 plates produces a five layer (0001) HCP plate, and subsequent plate thickening is accomplished by growth ledges which add four new layers of T_1 material on their passage across the broad face of the plate. In the absence of compositional faulting, the plates are always observed to consist of an odd number of (0001) layers.

13. Of the three chemical layers observed in the T_1 cell, the C layer (2:1, Al:Li) is always observed to be the interfacial layer. This suggests a lower interfacial energy for the C layer than that which would result from the A and B chemical layers.

14. T_1 plate nucleation can be modeled on the dissociation of a dislocation on opposite sides of a jog (or cross-slipped screw segment) one or two 111 planes high. Such dissociation will explain all of the observed characteristics of the T_1 plates. The transformation produces a five layer HCP plate by the coupling of partials on these layers, and the model can produce either perfect or imperfect stacking with displacement faults.

15. The influence of stretching will not only increase the number of dislocations, but also the number of dislocation jogs. The model of T_1 nucleation at jogs is, therefore, consistent with experimental observations derived from the plate distributions.

16. T_2 is the dominate grain boundary precipitate produced in 2090 type alloys in the temperature range 200-520°C.

The δ phase reported to occur (12) is not observed at any aging temperature or time studied. The δ' PFZs observed in material containing δ' are a result of the precipitation of the more stable T_2 phase at grain boundaries.

17. Mixed T_2 and R phase precipitation is observed at grain boundaries in material aged for various times between 150-190°C. Again, the δ phase is not observed.

18. T_2 has been determined in this investigation to be an icosahedral quasicrystal and to form by nucleation and growth as a solid-solid phase transformation.

The practical applications of this study are many. From a fracture toughness point of view, we have found that the T_2 phase is responsible for most of the undesirable fracture characteristics, and its formation should be discouraged. Similarly, the desirable strengthening component added by enhanced T_1 precipitation should be encouraged. Consequently, the best recommended treatment for optimizing properties of 2090-type alloys is to solutionize the material, quench, stretch between 4 and 6 percent, and subsequently age between 120-150°C to obtain the desired strength. Preaging at temperatures of 40-60°C for approximately 24-48 hours prior to higher temperature aging has some advantages for particular property enhancement.

B. **Heterogeneous Precipitation and Mechanical Properties in Al-Li-Cu-Mg Alloys:** From the experimental work performed during this study of heterogeneous precipitation in an Al-2.58Li-1.36Cu-0.89Mg-0.12Zr alloy the following conclusions may

be drawn:

1. S' precipitates may nucleate on the δ'/matrix interface. Because of the negligible misfit between the matrix and δ', this interface would not be expected to serve as a favorable site for S' nucleation. However, during the growth of δ' (Al_3Li) excess Cu and Mg concentrations occur at the growth front. This coupled with the excess vacancies released when Li adds to the δ' particle result in favorable conditions for S' nucleation.

2. S' also nucleates on matrix dislocations which may be induced by stretching after quenching, or on subgrain boundaries which may be present in unrecrystallized structures. Growth of the precipitates occurs by a ledge mechanism.

3. The cluster nucleation mechanism, which has been observed for S' in Al-Cu-Mg alloys, does not occur. This might be due to the high binding energy of Li to vacancies (13) which prevents supersaturation and collapse of the vacancy clusters to loops and subsequent dislocation climb to helices (14) which favor cluster formation sites.

4. Detailed inspection of atomic resolution micrographs, from alloys with and without Li, did not reveal two types of S-type precipitates (i.e. S and S'). This result reinforces the statement by Gregson and Flower (15) that unless a difference is noted between S and S', the notation should be dropped.

5. Deformation prior to aging of 8090-type alloys has an effect on S' precipitation similar to that observed for T_1 precipitation in 2090-type alloys; i.e. the number density of S'

precipitates is increased, the aging kinetics are enhanced, the size of S' at peak strength is reduced, and the obtainable peak strength is increased by deformation.

6. Deformation prior to aging does not appear to have a significant effect on the size or volume fraction of grain boundary precipitates as a function of aging time. However, since the stretch does have a significant effect on the aging kinetics of the matrix precipitates, peak strength is reached at earlier times in stretched material resulting in reduced size and volume fraction of grain boundary precipitates and thus an improved yield strength/ductility combination.

C. **Role of Vacancies on the Precipitation Processes in Zr-Modified Aluminum Alloys:** From the experimental results from this aspect of our program we may draw the following conclusions:

1. Trace additions of Zr to an Al-Zn-Mg alloy retards GP zones and η' formation, slows down η precipitation, and inhibits T phase nucleation.

2. An excess loss of vacancies to subgrain boundary sinks together with the modification in the distribution of free vacancies in solution are responsible for the effects mentioned in 1.

3. The distribution of free vacancies in solution are affected by the Zr-vacancy binding prior to quenching, and by the positive β'/α misfit associated with the coherent β' precipitates during aging.

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